

# The Performance of the First Optical Refrigerator

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**Abstract-** Optical refrigeration using anti-Stokes fluorescence in solids has several advantages over more conventional techniques, including low mass, low volume, low cost and no vibration. It also has the potential of allowing a miniature cryocoolers on the scale of less than a cubic centimeter. It has been the topic of analysis and experimental work by several organizations. In 2003, we demonstrated the first optical refrigerator. It cooled an attached load 11.8° C below the surroundings.

Our laboratory refrigerator is pumped by a 30 watt, tunable, ytterbium doped yttrium aluminum garnet (Yb:YAG), continuous wave, disk laser and uses a ytterbium doped glass fluorescent cooling element external to the laser cavity. The fluorescent element is connected to an aluminum load containing a silicon diode thermometer and heater. The fluorescent element rejects its heat to a sink in a high vacuum.

In this paper, we report on the operation of our laboratory optical refrigerator at different pump wavelengths, power inputs and loads. We have modeled the refrigeration cycle based on the fluorescent material emission and absorption data at ambient and reduced temperature. We have also modeled the heat transfer into the refrigerator cooling assembly due to radiation and conduction. The measured heat transfer and heat lift of the refrigerator is presented and compared to the expected performance

## I. INTRODUCTION

The basic principle of cooling by anti-Stokes fluorescence was suggested as early as 1929 [1], but it was not until 1995 that the actual cooling of a solid was first demonstrated by Epstein et. al. at Los Alamos National Laboratory (LANL) using Ytterbium doped Zirconium Fluoride (Yb:ZBLAN) glass [2,3]. In 1996, Clark and Rumbles reported cooling in a dye solution of rhodamine 101 and ethanol [4]. A collaborative effort by LANL and Ball Aerospace resulted in an isolated cylinder of Yb:ZBLAN cooling 48°C below the ambient temperature [5]. Gosnell has reported cooling of 65°C in a Yb:ZBLAN fiber [6]. In 2003, we demonstrated the first optical refrigerator. It cooled an attached load 11.8° C below the surroundings [7].

The fundamental refrigeration cycle of fluorescent cooling is simple. In the case of the Yb: ZBLAN material, the presence of the internal electric fields of the host ZBLAN material cause the ground and first excited states of the Yb<sup>3+</sup>

ion to be split into multilevel manifolds as shown in Fig. 1. A photon from a laser tuned appropriately will be absorbed only by an ion that has been thermally excited to the highest level of the ground-state manifold, and will promote that ion to the lowest level of the excited-state manifold. When that ion decays radiatively, it can fall to any of the four ground-state levels. On average the outgoing fluorescent photon will therefore carry slightly more energy than the pump photon absorbed. By selectively “picking off” the “hottest” ions, this process depletes the population of the highest ground-state level. Thermal equilibrium is reestablished when another ion is promoted to that level by absorbing a phonon from the host material. The absorption of this phonon constitutes the refrigeration.

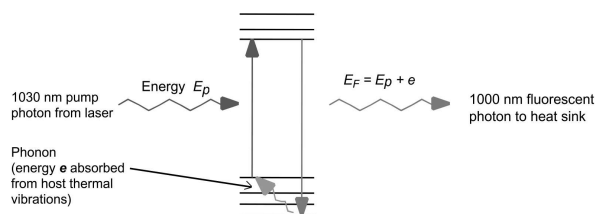


Fig. 1. The photon-phonon refrigeration cycle results from the energy levels of the Yb<sup>3+</sup> ion in the ZBLAN glass host material.

In summary, a Yb<sup>3+</sup> dopant ion absorbs a pump photon and the photon is re-emitted slightly bluer (higher energy). This energy difference comes from thermal vibrations (phonons) of host material.

The simplest implementation of a cryocooler based on this principle is a simple Yb:ZBLAN cylinder (cooling element) with high-reflectivity dielectric mirrors deposited on the ends as shown in Fig. 2. The pump beam is introduced through a small feed hole in one mirror, and then bounces back and forth until it is absorbed. A key feature of this arrangement is that the pump light is confined to a nearly parallel beam, while the fluorescence is emitted randomly into 4 $\pi$  steradians. This makes it possible to allow the fluorescence to escape while trapping the pump light inside. The fluorescent photons that are nearly parallel to the pump beam are also trapped. They are reabsorbed and then simply try again to escape with a small and calculable degradation to the overall efficiency.

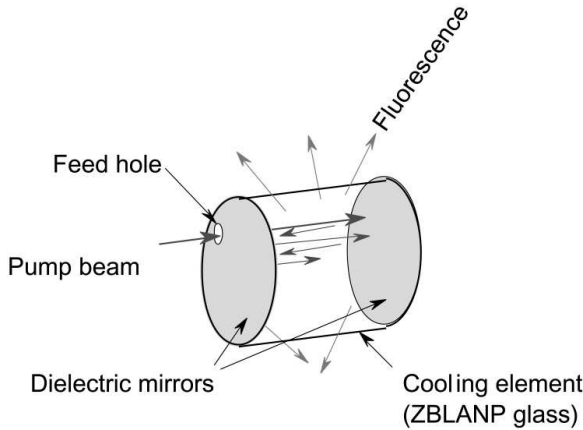


Fig. 2. Dielectric mirrors provide long pump path

The potential advantages of optical cooling have been identified in previous work [8]. The overall system mass for mechanical coolers, thermoelectric coolers and optical cryocoolers for an optimized spacecraft application were calculated. An optical cryocooling will likely have the lowest system mass when the load is less than 1.0 W and the temperature is between 80 and 200 K. Optical refrigeration has the potential to extend benefits of solid-state cooling a new, lower temperature region. Optical cryocooling can potentially be miniaturized to a much smaller level than conventional methods. We have a preliminary design for a cryocooler with a total volume of 0.3 cubic centimeters that could provide 3 milliwatts net refrigeration at 80 K. [9]

## II LABORATORY REFRIGERATOR DESIGN

A sketch of the laboratory optical refrigerator is shown in Fig. 3. The refrigerator is contained in a small vacuum chamber (not shown), which contains a window for the pump beam. The vacuum chamber is pumped to a pressure less than  $10^{-4}$  torr using a turbo molecular pumping station. The chamber is maintained at a constant temperature about 10 degrees C above the ambient to eliminate the effect of swings in the laboratory temperature. This allows for more precise measurements of heat conductance and cooling.

A copper heat sink completely surrounds the cooling assembly and is mounted to the vacuum chamber wall. A significant issue with the heat sink is the surface facing the cooling assembly. This surface needs to selectively absorb the near 1 micron fluorescence while having low emittance to the ambient radiation. The cooling assembly, which includes the fluorescent element, thermal link and the load mass, is mechanically supported within the heat sink using a fiberglass epoxy support.

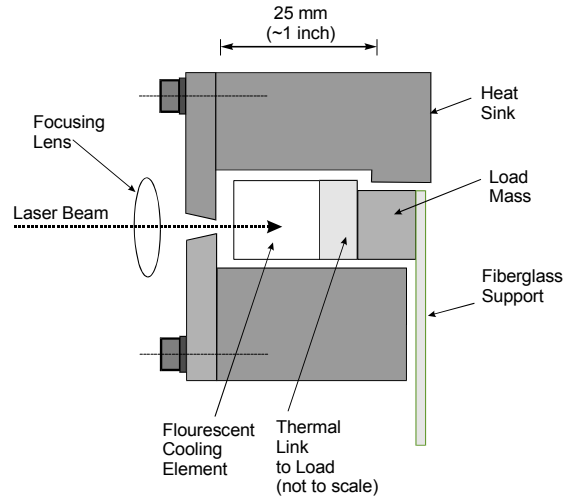


Fig. 3. Ball The laboratory optical refrigerator.

The fluorescent cooling element is made from Yb:doped Zirconium Fluoride glass (ZBLAN). It is cylindrical and coated on both ends with high performance dielectric mirrors. The fluorescent element is 12 mm in diameter and 13 mm long and weighs 8.5 grams. It is doped with 2% by mass Ytterbium Fluoride.

A critical issue in the design of an optical refrigerator is that the load to be cooled will invariably be light absorbing and must be shielded from the light from the cooling element fluorescence while being in thermal contact with it. This occurs even when the load appears to be shielded by one of the dielectric mirrors since has been found that the dielectric mirrors leak a significant amount of fluorescence [10]. The fluorescent element is attached to the load with a proprietary thermal link that provides high thermal conductance but prevents the leaked fluorescence from being absorbed by the load.

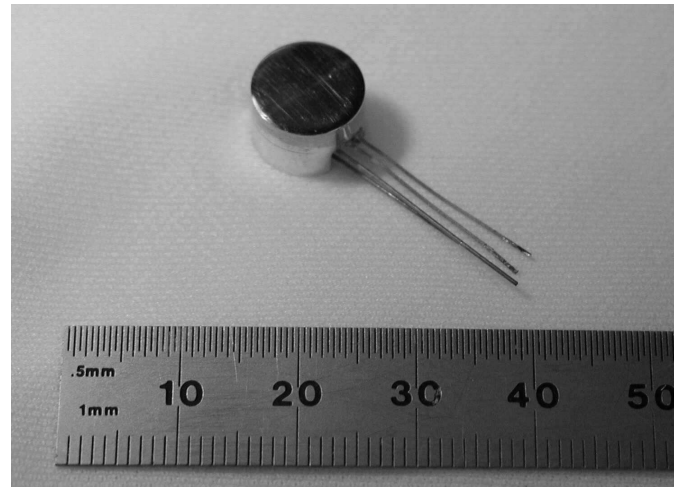


Fig. 4. A photo of the load mass. The top and sides have been polished and coated with gold and the heater resistor and silicon diode thermometer are bonded in a groove in the aluminum.

The load mass is intended to simulate a small infrared focal plane or other small sensor. It consists of an aluminum cylinder 10 mm in diameter and 6 mm thick and weighs 1.1 grams, Fig 4. A silicon diode thermometer and an 1/8 watt, 240 ohm, carbon resistor are mounted with adhesive in a slot in the load mass cylinder. The carbon resistor is used as a heater to impose a heat load and can also serve as a backup thermometer. Four, 36-gauge phosphor bronze wires are connected to the silicon diode thermometer and carbon resistor.

The fluorescent element was pumped using a commercial Yb:YAG disk laser, which could be tuned from 1015 to 1050. Tests were done at wavelengths of 1020 to 1040 nm. The could produce output powers of up to 25 watts but only near the 1030 nm optimum power wavelength. The laser powers reported here are our estimate of the laser power at fluorescent element, based on the power measured at the laser and measurement of the feed optics attenuation.

### III. TEST REFRIGERATOR PERFORMANCE

The test refrigerator was operated after carefully aligning and focusing the laser beam into the fluorescent element to achieve the maximum fluorescence as measured by a photodiode. The laser beam was then turned off, the vacuum chamber was pumped down and the cooling assembly was allowed to come into thermal equilibrium with the heat sink. The laser beam was then turned on and the temperatures of the load mass and heat sink were monitored. The beam remained focused on the fluorescent element until a near steady state condition was achieved. The beam was then turned off and the temperatures continued to be monitored.

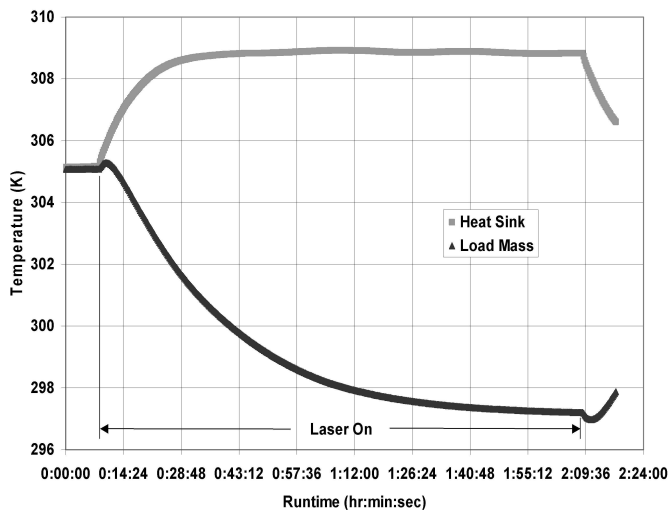


Fig. 5. Effect of pumping the fluorescent element with 7.4 watts of 1030 nm laser light for the indicated time period.

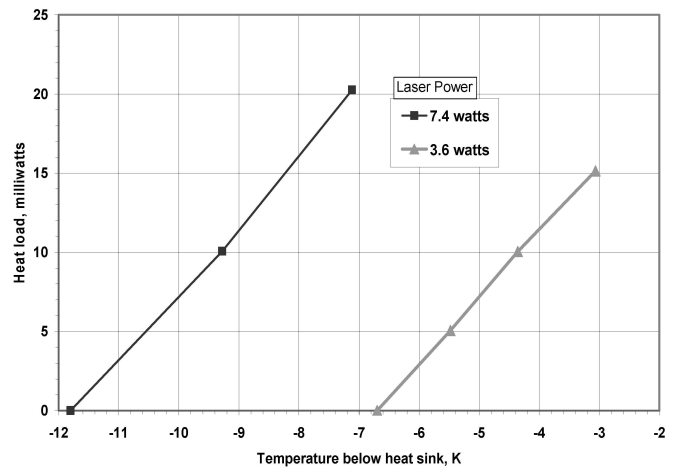


Fig. 6. Test refrigerator load curve for the laser powers shown and a wavelength of 1030 nm.

A typical result is shown in Fig. 5 for 7.4 watts of laser power. When the beam is introduced into the fluorescent element the load mass thermometer initially heats and then the cooling effect appears to take over and the assembly cools. When the beam is turned off, the assembly continues to cool for a brief period. We conclude from this, that there is a heat source that gets to the load mass very quickly once the beam is turned on and is eventually overwhelmed by the cooling effect of the fluorescent element.

The most likely explanation is that some fluorescence is still being absorbed by the load mass. The fluorescence being absorbed by the heat sink caused its temperature to rise until it came into thermal equilibrium with the chamber wall. At equilibrium, the load mass was cooled 7.9° below the starting temperature and 11.8° below the heat sink. The maximum steady state temperature measured was 15.6 °C for 14 watts of laser power.

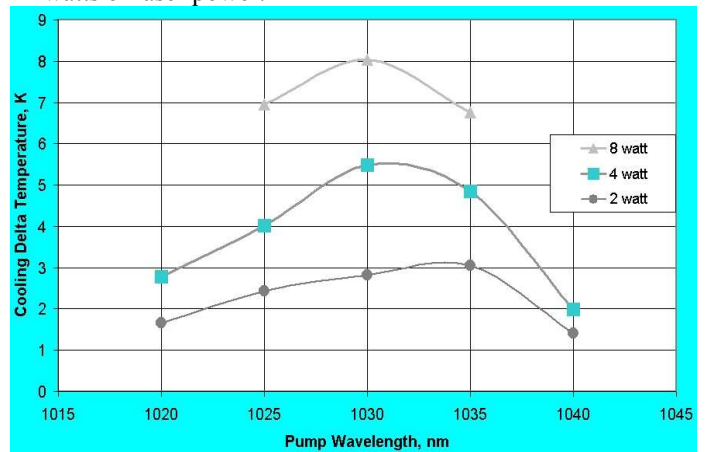


Fig. 7. Cooling delta temperature at various powers and wavelengths.

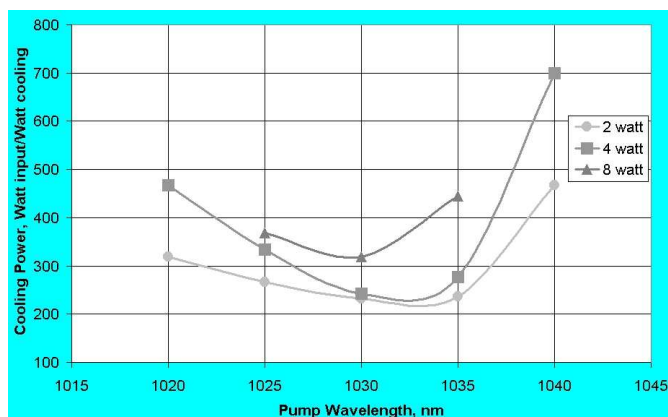


Fig. 8. Specific Cooling Power at various input powers and wavelengths

We also explored the heat loads that could be lifted by a cooling assembly, for a given laser power, by putting various electric powers through the resistor. The result is a load curve for the test refrigerator as shown in Fig. 6. The power was also applied to the resistor without having the laser on to measure the thermal conductance between the cooling assembly and the heat sink. This was determined to be 4.32 watts/K. When the cooling assembly was 11.8° below the heat sink, the refrigeration was 67.4 milliwatts.

Modifications were made to reduce the radiation heat transfer between the cooling assembly and the heat sink. The conductance between the cooling assembly and the heat sink was modeled using standard thermal modeling techniques. The value estimated by the model was 2.5 milliwatt/K which is 17% less than the 3.0 milliwatts/Kelvin that was measured.

The refrigerator was operated at a variety of powers and wavelengths. The resulting temperatures are shown in Fig. 7. As expected higher power levels produced increased cooling and lower temperatures. At all power levels, the maximum cooling occurred at 1030 nm. Based on the measured conductance of the cooling assembly to the sink the refrigeration power and a specific refrigeration was calculated by dividing into the input power. The results are shown in Fig. 8. As the input power was increased, the specific refrigeration was reduced. This was expected because as pump power, is increased, the electrons in the lower manifold are depleted.

## V. CONCLUSIONS

We have developed a method for thermally attaching the fluorescent element to a load mass, while isolating it from the mirror leakage. This has allowed us to demonstrate optical refrigeration of a load mass that simulates an infrared focal plane or other small sensor. We have also created a refrigerator test bed that will allow accurate tests of the refrigeration capacity of fluorescent elements.

Our laboratory optical refrigerator was operated at various wavelengths and powers. The optimum wavelength was found to be 1030 nm at all powers. Operation of our

laboratory refrigerator resulted in a maximum cooling of 15.6 degrees and a heat lift of 67.4 milliwatts. The highest specific cooling was 6.9 milliwatt/watt (145 watt input/watt cooling). As the input power was increased, the specific refrigeration was reduced.

Further work on cooling assembly packaging and fluorescence control may further reduce the effect of fluorescence heating. We anticipate substantially increased refrigeration and lower temperatures as these and other refinements are made and higher laser powers are used.

## ACKNOWLEDGMENT

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## REFERENCES

- [1] Pringsheim, P., *Z. Phys* 57, (1929), p. 739.
- [2] Epstein, R.I., M.I. Buchwald, B.C. Edwards, T.R. Gosnell and C.E. Mugan, "Observations of Laser-Induced Fluorescent Cooling of a Solid," *Nature* 377, 500 (1995)
- [3] Epstein, R.I., et al., "Fluorescent Refrigeration," U.S. Patent. No. 5,447,032 (University of California).
- [4] Clark, J.L., G. Rumbles, *Phys. Rev. Letters*, 76, 2037 (1996).
- [5] Edwards, B.C., J.E. Anderson, R.I. Epstein, G.L. Mills, and A.J. Mord, "Demonstration of a Solid-State Optical Cooler: An Approach to Cryogenic Refrigeration," *Journal of Applied Physics*, 86 (1999).
- [6] Gosnell, T.R. "Laser Cooling of a Solid by 65 K Starting from Room Temperature," *Optics Letters*, vol. 24, no. 15 (1999).
- [7] Mills, G.L., Turner-Valle J. A., Buchwald M.I., "The First Demonstration of an Optical Refrigerator", Cryogenic Engineering Conference, Sept. 2003, Anchorage, AK
- [8] Mills, G.L., Mord, A.J., Slaymaker. P. A., "Design and Predicted Performance of an Optical Cryocooler for a Focal Plane Application", *Cryocoolers 11*, Keystone, CO, June 2000 pp 613-620
- [9] Mills, G. L., "Progress in Optical Refrigeration", Fourth Workshop on Military and Commercial Applications of Low-Cost Cryocoolers", November 20-21, 2003, San Diego, CA.
- [10] Mills, G. L., Fleming J. , Wei Z., Turner-Valle, J.A., "Dielectric Mirror Leakage and its Effects on Optical Cryocooling" *Cryocoolers 12*, Cambridge, MA,, 2002